Initial State Energy Loss Dependence of J/Ψ and Drell-Yan in Relativistic Heavy Ion Collisions

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Abstract

We present a Glauber-based study of J/Ψ and Drell-Yan yields in nucleus-nucleus collisions. Using this approach, we have investigated the impact of energy loss by the colliding nuclei on observed yields and transverse momentum spectra of J/Ψ and Drell-Yan. These studies permit an assessment of the importance of initial state energy loss in relation to "anomalous" J/Ψ suppression.

1   Introduction

The yield of J/Ψ particles in relativistic heavy ion collisions is a subject of considerable current experimental and theoretical work. It has been predicted that in the case of a phase transition to a quark-gluon plasma, the yield of J/Ψ particles is suppressed due to Debye screening [1]. The level of suppression of J/Ψ yields can be benchmarked in the context of a simple theoretical framework. A Glauber model is employed where each nucleon-nucleon collision is assumed to have an equal probability to produce a $c\bar{c}$ pair. This $c\bar{c}$ pair may then form a quarkonium state; alternatively, the initially produced $c\bar{c}$ pair can undergo inelastic interactions while traversing the nuclear medium, reducing the final J/Ψ yield. Measurements of J/Ψ yields from $p-A$ interactions [2,3] and $A-A$ interactions [4,5] for beams of $A \leq 32$ are well described in this

model by an absorption cross section of 6-8 mb. This cross section is consistent with calculated values [6] if the absorption occurs not on a color singlet $c\bar{c}$ pair, but rather on a $c\bar{c} - g$ color octet state. However, recently the NA50 experiment has measured the J/Ψ yield in $Pb - Pb$ collisions at 158 AGeV/c as a function of the transverse energy produced in the collision in which the data appear to be inconsistent with a Glauber-based model including only the 6-8 mb absorption on nucleons [7]. This difference is referred to as "anomalous" J/Ψ suppression and has been interpreted by some as evidence for the deconfinement transition [5].

However, without invoking deconfinement, other physical processes can and have been added to the above simple model. Once the $c\bar{c}$ pair has hadronized into a specific quarkonium state, it may also undergo inelastic interactions in the high density medium dominated by mesons (often referred to as co-movers), thus producing open charm in the form of D mesons. Many studies indicate that these cross sections are quite small relative to the expected disassociation in a deconfined state with free quarks and gluons [8]. Model extensions including interactions with co-movers are discussed in [9]. In addition, the possible contributions of gluon shadowing [10] and enhanced charm production may play a role. It has also been suggested that initial state energy loss may explain the suppression of J/Ψ [11].

In their most recent paper [12], the NA50 collaboration has claimed that in the ratio of J/Ψ to Drell-Yan a "clear onset of the anomaly is observed as a function of transverse energy. It excludes models based on hadronic scenarios since only smooth behaviors with monotonic derivatives can be inferred from such calculations." This statement would imply that further investigation into explanations involving co-movers, initial state energy loss, *etc.* are not necessary. Although deconfinement may eventually be considered the correct explanation, we feel this conclusion is premature. Several studies have described some subset of the data reasonably well with various hadronic descriptions [9–11]. However, detailed studies of hadronic scenarios which compare to all of the available data have yet to be fully carried out, and this must be done before any real conclusions can be drawn.

In this letter, we detail a study of initial state energy loss and its impact on both the transverse energy dependence and the transverse momentum spectra of J/Ψ and Drell-Yan. In a recent report [11], the inclusion of initial state energy loss into a Glauber model was shown to match the J/Ψ yield measured by NA50 in $Pb - Pb$ minimum bias (*i.e.* averaged over all impact parameters) collisions; this agreement led to the interpretation that initial state energy loss was the source of the "anomalous" J/Ψ suppression. Here we extend the comparison to include the centrality dependence of the yields and p_t spectra of both J/Ψ and Drell-Yan. By looking at the details of the entire available data set, we hope to resolve the question of whether initial state energy loss

can explain "anomalous" J/Ψ suppression.

2 Calculations

In the absence of absorption and energy loss, all individual $N - N$ collisions within an $A - A$ interaction are equally likely to produce a detected J/Ψ. However, due to absorption, those nucleons on the trailing edges of the colliding nuclei are the most likely to produce a J/Ψ which will survive to be detected. This can be seen clearly in the left-hand panel of Figure 1, where the production position within the colliding nuclei of surviving J/Ψ is plotted, and only the absorption process has been included. As beam nucleons pass through the target nucleus, they lose energy via inelastic interactions, so that collisions between those nucleons on the trailing edges of the nuclei, where the geometry is most favorable for a produced J/Ψ to evade absorption, have considerably less than the full beam energy. Since J/Ψ production has a very steep energy dependence [13], these collisions are the least likely to produce a J/Ψ. Thus, nucleon energy loss will certainly reduce the observed yield of J/Ψ. This can be seen in the right-hand panel of Figure 1, where the production position within the colliding nuclei of surviving J/Ψ is plotted, and both initial state energy loss and absorption has been included. Moreover, the ratio of J/Ψ to Drell-Yan, which is often used to gauge J/Ψ suppression, could have a complicated centrality dependence, since Drell-Yan does not suffer from the geometrical predisposition caused by absorption. Finally, energy loss will also affect the p_t spectrum of J/Ψ–the trailing edge collisions which are most affected by energy loss are those which, via the Cronin effect [14], produce J/Ψ with the highest mean p_t.

In order to study initial state energy loss, we have constructed a Glauber model of nuclear collisions. We will describe the model briefly here; more details are available elsewhere [16]. Nucleons are distributed using a Woods-Saxon parameterization, and interact with a nucleon-nucleon cross section of 30 mb. As nucleons undergo interactions, they lose energy. Various models of energy loss are reasonably consistent with measured proton spectra in $p - A$ collisions; we have utilized a parameterization where nucleons lose a constant fraction of their momentum in each interaction. In order to match measured data, the momentum fraction lost per interaction would be ∼40%. However, most of this energy loss occurs via soft interactions, with a time scale of a few fm/c. At SPS energies, the colliding nuclei cross in ∼0.1 fm/c; thus, only a fraction of the time-integrated total energy loss is applicable to hard interactions. Our approach is to treat the applicable fraction of total energy loss as a variable parameter. The values we have chosen are 5%, 10% and 15% momentum loss per collision, to be compared with the 40% loss realized as the time between collisions approaches ∞. By counting the number of prior collisions for each
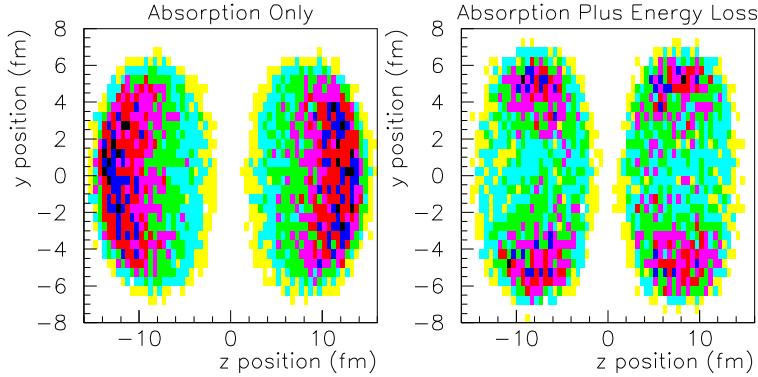
Fig. 1. Side view of colliding Pb nuclei, just before interaction. Positions are given in z (along the beam axis) and y, transverse to the beam; a slice has been taken in x to remove trivial projective density effects. The darkness of the pixels indicates the likelihood of J/Ψ production and survival. The plot on the left includes only absorption, while the plot on the right includes both absorption and initial state energy loss.

nucleon, a center-of-mass energy can be calculated for each $N-N$ interaction. This energy is used to calculate the relative probability that a J/Ψ or Drell-Yan pair will be produced, using the Schuler parameterization [13] for the J/Ψ energy dependence and "tau scaling" [15] for Drell-Yan energy dependence.

Produced J/Ψ are taken to be at rest in the $N-N$ center-of-mass frame, such that the survival probability is a function of the path length through nuclear material which the J/Ψ must traverse, the nuclear density and the breakup cross section. We have utilized a breakup cross section of 7.1 mb, which is $\sim$15% higher than the value of 6.2 ± 0.7 mb reported by NA50 [7]. The NA50 value is calculated by fitting the J/Ψ to Drell-Yan ratio as an exponential function of L, the mean path length through the nuclear medium, for various centrality bins in $p-A$ and $A-A$ collisions. Due to absorption, all possible path lengths do not contribute equally to the *actual* mean path length for surviving J/Ψ in a given centrality bin; thus, as we have shown elsewhere [16], a simple linear average over path lengths systematically underestimates the absorption cross section.

Shown in Figures 2 and 3 are the calculated yields of J/Ψ and Drell-Yan, respectively, from $Pb-Pb$ collisions, plotted as a function of transverse energy E_t, and compared to the NA50 measured values [7]. We have simulated the NA50 E_t bins, assuming E_t scales as the number of wounded nucleons and smearing the calculated values by the NA50 resolution of $94\%/\sqrt{E_t}$ [17]. For each figure, the yield without energy loss is shown in the leftmost panel, as well as that for our nominal choices of 5%, 10% and 15% momentum loss per $N-N$ collision. Our model does not predict absolute yields, so the normalization for each curve has been chosen so as to best match the NA50 data in the lowest E_t bins. Clearly, the J/Ψ yield deviates significantly from the prediction with
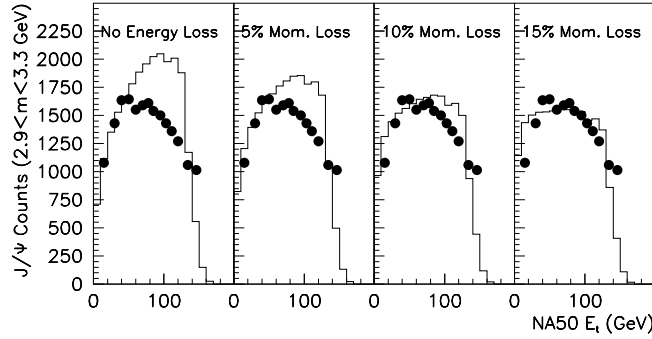
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Fig. 2. Comparison of Glauber model calculations (line) to J/Ψ yields from $Pb-Pb$ collisions as measured by NA50 (points), plotted as a function of E_t. The various panels show different values of initial state energy loss in terms of momentum fraction lost per $N-N$ collision.

no energy loss; although not shown here, the discrepancy is significant even if one increases the J/Ψ breakup cross section as high as 9 mb. This plot shows, in the simplest way, the additional suppression seen in the $Pb-Pb$ data as compared to expectations based on lighter systems. In the following panels of Figure 2, it can be seen that as energy loss is invoked, the prediction comes closer to the data, until for the maximum value of energy loss we consider, the prediction matches the data relatively well.

However, the scenario for Drell-Yan is considerably different, as shown in Figure 3. The prediction for no energy loss matches the data very well, while with just 5% momentum loss per collision, the prediction deviates significantly from most of the data points. For the maximum value of energy loss, which is necessary to match the J/Ψ yields, the prediction does not come close to matching the data. Thus, there is an inconsistency–the model can be forced to match the J/Ψ data by invoking a fairly large amount of energy loss, but this same value of energy loss causes the model to substantially underestimate the Drell-Yan yields. However, it is possible that this inconsistency could be explained away if the energy loss of gluons, which may dominate J/Ψ production, is different from that of quarks and antiquarks, the mutual annihilation of which lead to Drell-Yan production; whether this is the case remains an open question. It should be noted that precision studies of how energy loss affects Drell-Yan in $p-A$ collisions are also being done [18,19].

Another way to consider the effects of energy loss is to look at the p_t spectra of J/Ψ. The $\langle p_t^2 \rangle$ of J/Ψ from $p-A$ collisions has been observed to be larger than that from $p-p$ collisions. This increased p_t is understood [14] to come from an increase in the intrinsic transverse momentum of the partons in the colliding nucleons as a result of prior interactions. This mechanism, referred
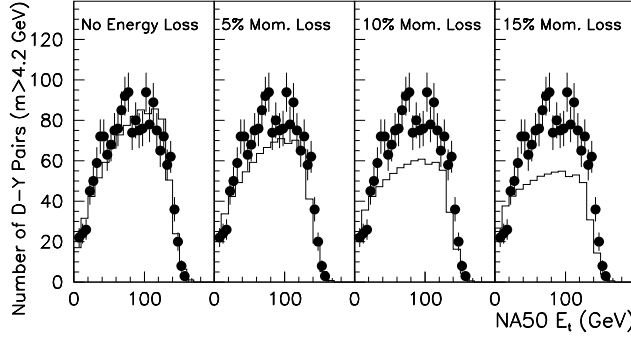
Fig. 3. Comparison of Glauber model calculations (line) to Drell-Yan yields from $Pb - Pb$ collisions as measured by NA50 (points), plotted as a function of E_t. The various panels show different values of initial state energy loss in terms of momentum fraction lost per $N - N$ collision.

to as the "Cronin effect", has been phenomenologically described by

$$\langle p_t^2 \rangle_N = \langle p_t^2 \rangle_{pp} + N \Delta p_t^2, \tag{1}$$

in which the $\langle p_t^2 \rangle$ of J/Ψ produced in a nucleon-nucleon collision where the colliding partners had a total of N prior interactions is given by the sum of the $\langle p_t^2 \rangle$ value from $p - p$ collisions plus N times Δp_t^2, the change in $\langle p_t^2 \rangle$ per collision. Thus, J/Ψ with the highest mean p_t come from the latest collisions, and are the most sensitive to effects coming from nucleon energy loss.

For J/Ψ, a value of $\langle p_t^2 \rangle_{pp} = 1.23 \pm 0.05$ GeV^2 was measured by NA3[20] at a beam momentum of 200 AGeV/c; however, before we can use this value, we must correct for the beam energy, since the SPS Pb beams are at 160 AGeV/c. Measured $\langle p_t^2 \rangle$ for Drell-Yan from pion and proton induced reactions on nuclei have been shown[21] to scale linearly with s, the square of the center-of-mass energy, with similar slopes for the two incident particle species. Measurements of $\langle p_t^2 \rangle$ for J/Ψ from proton induced reactions are scarce, but if one combines data from both pion and proton induced reactions[20], a linear scaling with s fits the data reasonably well. Using this slope, we estimate the value of $\langle p_t^2 \rangle_{pp}$ for interactions at 160 AGeV/c to be 1.13 GeV^2. A recent study[22], combining J/Ψ data from $p - A$ and $A - A$ interactions at 200 AGeV/c and using the measured value of $\langle p_t^2 \rangle_{pp}$ given above, performed a fit to determine a value for Δp_t^2 of 0.125 GeV^2.

Using these parameters, we have implemented the Cronin effect in our model. Transverse momentum distributions are taken to follow the usual form of $\frac{dN}{dm_t} \propto m_t \exp(-\alpha m_t)$. The prescription for the Cronin effect characterizes the transverse momentum after N collisions in terms of $\langle p_t^2 \rangle_N$, which is related to
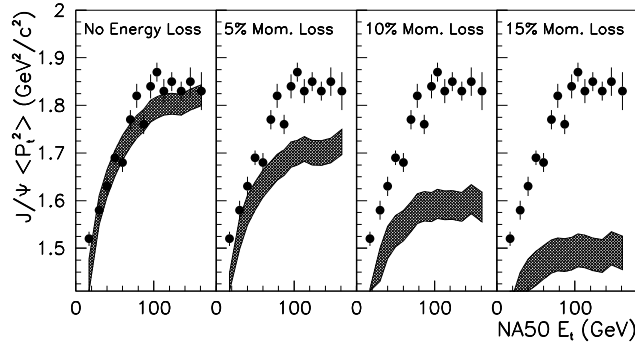
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Fig. 4. Glauber model calculations (shaded band) of J/Ψ $\langle p_t^2 \rangle$ from $Pb-Pb$ collisions, compared to NA50 measured data (points), plotted as a function of E_t. The width of the shaded band indicates the uncertainty in the measured value of $\langle p_t^2 \rangle$ from pp collisions, which has been energy scaled (see text). The various panels show different values of initial state energy loss in terms of momentum fraction lost per $N-N$ collision.

a slope parameter α_N by

$$\langle p_t^2 \rangle_N = \frac{2}{m\alpha_N + 1} \left[\frac{3}{\alpha_N^2} + \frac{3m}{\alpha_N} + m^2 \right] \tag{2}$$

for a particle of mass m. In practice, we wish to convert $\langle p_t^2 \rangle_N$ to α_N; over the $\langle p_t^2 \rangle$ range of interest and for the J/Ψ mass, the inverse of Equation 2 is well approximated by a power law, $\alpha_N \approx 6.68 \times \langle p_t^2 \rangle_N^{-0.855}$. In the course of the Glauber calculation, a p_t value is chosen from the appropriate distribution (based on the number of prior $N-N$ collisions for the interacting nucleons) for each produced J/Ψ. For those J/Ψ which evade absorption, a running value for $\langle p_t^2 \rangle$ is tabulated as a function of the total E_t of the collision.

The prediction for J/Ψ $\langle p_t^2 \rangle$ from $Pb-Pb$ collisions is compared to the NA50 data in Figure 4. The prediction is shown as a band of values, corresponding to the uncertainty in the scaled value of $\langle p_t^2 \rangle_{pp}$. The prediction with no energy loss matches the NA50 data quite well; this result is at odds with other recent studies [7], in which it has been claimed that a plasma was required in order to match the NA50 data. However, these calculations did not include a beam energy rescaling of the value for $\langle p_t^2 \rangle_{pp}$. There is some uncertainty in the scaling we have implemented, so that the question of matching the NA50 data is still open; however, given the normalization uncertainty involved, it seems premature to rule out a normal hadronic description of the NA50 $\langle p_t^2 \rangle$ data.

It is clear, however, that the inclusion of energy loss causes the prediction to deviate severely from the data. For a value of 15% momentum loss per collision, which gave the best match to the J/Ψ yields, the prediction for $\langle p_t^2 \rangle$ is in severe disagreement with the data. Thus, again we have an inconsistency;

in this case, a single value of energy loss cannot describe both the J/Ψ yields and the $\langle p_t^2 \rangle$ data. Since this discrepancy is between two aspects of the energy dependence of J/Ψ, it is not so easily dismissed.

3   Conclusions

In summary, we have performed an evaluation of the importance of initial state energy loss with respect to J/Ψ suppression. Within the uncertainty in normalization, the J/Ψ $\langle p_t^2 \rangle$ spectrum seems consistent with a normal hadronic scenario. The addition of energy loss can cause the model prediction to fit the J/Ψ yields; however, a single value of energy loss per collision cannot simultaneously match both the J/Ψ and Drell-Yan yields, nor can it simultaneously match both the J/Ψ yields and the J/Ψ $\langle p_t^2 \rangle$ data. This result suggests that, contrary to the proposal made elsewhere [11] based on minimum bias J/Ψ yields only, "anomalous" J/Ψ suppression cannot be explained by initial state energy loss. Clearly the simplest hadronic model does not match the $Pb - Pb$ J/Ψ yields, so that some other mechanism must be causing the increased suppression. However, before one can either claim or rule out any source of this effect, whether "normal" hadronic or otherwise, a systematic comparison to all of the data, as we have attempted to do here, must be performed.

4   Acknowledgements

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